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Field Trial and Laboratory Evaluation of Concrete Containing a Granulated Iron Blast Furnace Slag

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FIELD TRIAL AND LABORATORY EVALUATION OF CONCRETE CONTAINING A GROUND GRANULATED IRON BLAST FURNACE SLAG

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1. ABSTRACT

Tests were carried out in the field and the laboratory to evaluate the properties of concrete containing a ground granulated iron blast furnace slag* commercially produced in Ontario. The Slag was used as a partial replacement for portland cement*.

The Slag concrete and the control concrete had similar strength and durability characteristics, the only significant differences occuring in early age concrete strengths when the Slag concrete was significantly lower in strength than the control concrete.

Partial replacement of portland cement with the Slag did not significantly affect the mixing, placing and finishing of the concrete in a bridge deck.

It is recommended that Slag be accepted in Ministry structural and pavement concrete in the proportion of three parts portland cement and one part Slag. A greater fraction of Slag to total cementitious material may be acceptable for some construction. It is proposed to carry out further testing following a period of field experience with the 3:1 blend.

Since Slag costs less than portland cement the main advantage to the Ministry in allowing the use of Slag is a reduction in the cost of concrete construction.

*Note: In this report Normal Portland Cement (Type 10) is referred to as NPC and the ground granulated iron blast furnace slag is referred to as Slag.

2. OBJECTIVE

The objective of the field trial was to evaluate in bridge deck construction the effect on the properties and performance of concrete, of Slag as a replacement for 25 percent of the portland cement. Tests carried out on 30 MPa concrete from two deck slabs, one containing Slag, included:

- Slump and Air Content
- Bleeding
- Time of Setting
- Heat of Hydration
- Compressive, Flexural and Tensile Strength
- Pulse Velocity
- Scaling Resistance to Deicing Chemicals
- Parameters of the Air Void System in Hardened Concrete

The objective of the laboratory tests was to determine on concrete compressive and tensile strengths, the effect of 25 percent and 50 percent Slag replacement of the portland cement. The test program included two classes of concrete (30 and 35 MPa), two chemical admixtures (types WN and R) and two sources of Type 10 cement.

3. INTRODUCTION

In 1973 National Slag Ltd., Hamilton, and Red-D-Mix Concrete Ltd., Hamilton, offered the Ministry a Slag to be used as a partial replacement of NPC in concrete. It was suggested to the Ministry that if Slag was substituted for 25 percent of the NPC, the compressive strength of the concrete at later ages would increase by approximately 10 percent over that of the 100 percent NPC concrete, and also that the addition of the Slag would not change other characteristics of the concrete, i.e. freeze-thaw durability, shrinkage, etc. It was stated that the early strengths of the blended concrete would be somewhat less than that of the 100 percent NPC concrete. The two companies noted that the use of Slag in concrete would utilize energy that had already been spent and that a considerable overall energy reduction in concrete production would be achieved. The Ministry carried out a program of laboratory tests with the Slag concrete in 1974 and the results were tabled in an MTC report written by B. Chojnacki, - "Partial Replacement of Portland Cement With Pelletized Slag".(1) The report did not recommend the use of Slag in the Ministry's projects as there was no price advantage to the Ministry, and Slag concrete would not be suitable where high early strength and resistance to salt scaling was required.

During 1977, a small scale field trial (2) was initiated on MTC Contract 76-117 on Highway 3 at Port Colbourne, where six concrete mix designs incorporating various ratios of NPC and Slag in 25 and 30 MPa concrete were compared for durability in curb and gutter construction. As of May, 1982, the six test sections and the control section have shown no deterioration. Most of the field fabricated salt scaling slabs tested in the laboratory exhibited satisfactory durability.

The 1977 field trials and the work described in this report were carried out following changes by the manufacturer to some of the properties of the Slag and against a background of a widening difference in the cost of NPC and Slag.

3. INTRODUCTION (Cont'd)

In 1980 the Ministry chose twin structures, then being constructed across the Sydenham River at Strathroy (Hwy. 402, Contract 79-51) for a full scale field evaluation of Slag as a 25 percent replacement for NPC. The concrete deck of the westbound structure was placed using 100 percent NPC, the deck of the eastbound structure was placed using 75 percent NPC and 25 percent Slag. This field trial plus a laboratory testing program is the subject of this report.

4. HISTORICAL BACKGROUND ON THE USE OF SLAG

The hydraulic properties of slag were first studied in France in the 1700's. Germany began to use slag for cementitious purposes in 1822, and granulated slag plus lime in 1863. Similar uses for slag were developed in other industrial countries, and by 1892 slag was interground with cement clinker to form "Portland Blast Furnace Slag Cement". In the eastern United States just prior to World War 1, production of slag plus lime, called "Slag Cement" became a thriving industry, and production reached 10 percent of the U.S. total cement production, before misuse of the material effectively destroyed the market. Many U.S. specifications then prohibited the use of slag in order to prevent the marketing of air cooled slag with large quantities of accelerators as "Portland Cement". After World War 2 cement manufacturers alleviated their material shortages by intergrinding granulated slag with portland cement clinker, and specifications for "Blended Hydralic Cement" were developed. It was demonstrated that these cements were the equivalent of good quality "Portland Cements" both in initial concrete properties and in field performance. It was recognized (3) that the best hydraulic properties were achieved when the molten slags had a high glass content and were properly granulated. As the cement industry increased its production capacity it reduced the amount of slag it incorporated into cement.

In the 1960's South Africa commenced the first commercially successful separate grinding of Slag. N. Sutterheim (4) reported that the separate grinding of the slag gave better production quality control of the product fineness, it stored better, and as it could be added as a separate ingredient to the concrete, the proportioning was at the discretion of the user, and could be optimized for individual job conditions. The South African product is called "Slagment" and it was first used bag for bag with Portland cement, on a "50 50" basis for ease of batching. 1980 production is estimated at 500,000 tonnes. Slagment is mandatory in some South African specifications. Motivated by the potential for energy conservation (5) the United Kingdom, Canada, Japan and the U.S.A. have followed South Africa and have commenced the separate grinding of granulated iron (6) blast furnace slag. Currently at Sparrows Point, Maryland, a granulating and grinding operation is under construction with a capacity of 800,000 tonnes per year.

The Standard Slag Cement Company at Fruitland, Ontario, produced the first commercial Slag in Canada. The ball mill plant capacity was 100,000 tonnes and the first year's production (1976) was 50,000 tonnes. The granulated iron blast furnace slag source used is Dofasco, Hamilton, Ontario. National Slag Ltd., Hamilton, Ontario, produce a pelletized granulated slag from the Dofasco product. The modified pelletizer produces a granulated slag having a minimum glass content of 90 percent when tested using the South African method. The average degree of granulation achieved is 96 percent. This granulated slag is dried and ground by the Standard Slag Company to a Blaine fineness of approximately 400 m^2/kg with 80 percent passing the 45 μm sieve. Initially the product was used internally for field evaluation within the various divisions of the parent company, Standard Industries Ltd. By March, 1979, considerable experience of product performance had been gained, and the Slag was placed on the open construction market. The Slag is shipped by tanker truck to ready mix concrete plants, concrete pipe plants, etc. and is stored in separate silos until it is incorporated into the concrete mix, in the proportions required by the customer. This technique permits the amount of Slag used to be varied to suit job conditions and requirements.

Anticipating a need for a higher production volume of Slag, the capacity of the Fruitland plant was recently doubled to 200,000 tonnes per year by installing an additional grinding mill and a Slag cooling system. In 1980 this plant produced 90,000 tonnes of Slag, most of it being sold to customers in the Hamilton, Toronto, area.

In Canada at the present time two C.S.A. Standards cover the use of Slag:

A362-M1977 Blended Hydraulic Cement
A363-M1977 Cementitious Hydraulic Slag

5. EVALUATION OF SLAG IN CONCRETE

A. Field Trial Program

The purpose of the field trial program is established in the "Objectives".

Test Methods and Construction

i) Test Methods

The following are the properties of the NPC - Slag combinations examined, and the test procedures used:

Slump	CAN3-A23.2-5C
Air Content By Pressure Method	CAN3-A23.2-4C
Bleeding	ASTM C-232
Time of Setting	ASTM C-403
Heat of Hydration	ASTM C-186
Compressive Strength	CAN3-A23.2-9C
Flexural Strength	CAN3-A23.2-8C
Tensile Strength	CAN3-A23.2-14C
Pulse Velocity	ASTM C-597
Scaling Resistance to Deicing Chemicals	MTC Procedure
Air Void System By Linear Traverse	ASTM C-457

ii) Construction

The field trial was the construction of the deck slabs on two similar, single span, structures spanning the Sydenham River, Highway 402. 30 MPa concrete was placed in the reinforced concrete deck slabs on these structures on consecutive days. The location of the field test is shown in Figure 1.

The deck for the westbound structure was cast on May 21, 1980, using the control concrete containing 100% NPC. The deck for the eastbound structure was cast on May 22, 1980, using the test concrete containing 75% NPC and 25% Slag. Similar spring ambient temperatures of approximately 18^{o}C, and good weather conditions prevailed during the construction of these decks.

The concrete mix proportions used in the field trials are presented in Table 6.

Concrete was delivered to both structure decks from the Red-D-Mix Co. concrete batching plant in the Town of Strathroy, which is located approximately five kilometres from the Sydenham River construction sites. The batching plant was equipped with separate silos to store NPC and Slag. Samples of the NPC and Slag delivered to the batching plant were sent to the Ontario Research Foundation laboratories to be tested for their heat of hydration characteristics.

Concrete delivery each day commenced at 8:00 a.m. and finished approximately at 1:00 p.m. Random loads of concrete to be delivered to the structure deck slabs were tested at the plant for air content and slump. The plant had the facilities and equipment required under MTC Form 1350.10.01 to determine the moisture content of the aggregates, but in fact the moisture contents were only estimated.

On both days of the trial program one load of concrete was selected at random at the plant and subjected to extra testing, to compare various characteristics of the two concretes.

The two loads so selected were:

i) the control, 100% NPC concrete, load 7, which had an air content of 5.0% and a slump of 60 mm

ii) the test, 75% NPC, 25% Slag concrete, load 3 which had an air content of 7.3% and a slump of 80 mm

It was unfortunate that the two loads of concrete had significant differences in air content, since this characteristic affects some of the properties under test. In general the increased air content of the test concrete (75% NPC, 25% Slag) can be expected to reduce bleeding and concrete strength, and increase scaling resistance compared to the control concrete (100% NPC) with the lower air content.

Concrete from the two loads was tested for the following characteristics:

Bleeding	Fig. 15	Plant Sample
Time of Setting	Fig. 14	Plant Sample
Heat of Hydration	Table 12	N/A
Compressive Strengths, 7, 14, 28 and 90 days	Table 11	Site Sample
Flexural Strength	Table 9	Plant Sample
Tensile Strength	Table 9	Site Sample
Pulse Velocity	Table 11	Site Sample
Scaling Resistance to Deicing Chemicals	Figs. 12 & 13	Site Sample

The travelling time of the agitating trucks from the plant to the site was approximately 10 minutes. On arrival at the site, and prior to placement of concrete into the deck each load of concrete was tested for slump and air content, except for the 1 m^3 make up load number 13 of the control concrete delivered on May 21st. Load number 5 of the 75% NPC 25% Slag test concrete delivered on May 22nd was rejected because the testing showed that it had an unacceptably high slump. All the remaining concrete delivered to the site was accepted in spite of the fact that many slump test results did not meet the Ministry requirements detailed in MTC Form 1350.05.02, Table 2. The air contents for all loads of concrete for both the control 100% NPC and the test 75% NPC 25% Slag concretes at the time of placing met MTC requirements.

After the concrete was tested and accepted it was then discharged directly from the truck into the hopper of a Schwing concrete pump and pumped into the decks of the structures.

Cylinders were cast from concrete sampled at the site from all concrete accepted for placement in the decks of the structures. The results of the testing of these cylinders in compression at 28 days is shown in Table 7.

The maximum distance any concrete was pumped was 30 m. A standby crane and bucket was available in case of pump breakdown. During pumping of the test concrete a 20 minute pump breakdown occurred, whilst the piston was replaced. The crane and bucket was also used to place the concrete near the mid point of each structure deck, to reduce the pumping distance. Some reduction in pump operating pressure was observed when the test concrete was pumped compared with that of the control concrete.

The approximate location of each load of concrete placed in both decks was recorded so that the appropriate air tests on the plastic concrete could be compared with the air void characteristics of cores taken from the hardened concrete. The results of this testing are shown in Table 10.

The concrete was consolidated using hand held internal poker vibrators, and struck off and finished using a Bidwell bridge deck finishing machine. The final finish applied to both decks was a bullfloating from a workbridge. Since the deck slab is to be waterproofed and paved, the concrete surface was not textured. The screed rails which supported the Bidwell finishing machine were removed as soon as possible. The screed rail chair supports were removed from the plastic concrete and the deck concrete at these locations was quickly refinished by hand. Both the control and test concretes exhibited good finishing characteristics. After the minor bleeding of the concretes ceased, both deck slabs were cured using a membrane curing compound.

The day following construction, and after curing on site, all cylinders, slabs and beams were delivered to the MTC Southwestern Region laboratory for moist curing prior to testing.

B. Laboratory Test Program

The laboratory test program was designed to evaluate the effect of a higher Slag replacement value than that used in the field, and to measure concrete strength properties, particularly early age strengths, with additional admixture types, cement sources, and cement content.

The laboratory program was carried out at the MTC Downsview concrete laboratory and consisted of twenty-four batches of concrete utilizing two Type 10 Portland cements, two chemical admixtures, 30 MPa and 35 MPa classes of concrete, and the following ratios of cementitious materials:

100% NPC
75% NPC 25% Slag
50% NPC 50% Slag

Nine cylinders were obtained from each batch of concrete. Two cylinders were tested in compression at 3, 7, 28 and 90 days, and one cylinder from each batch was tested in tension by the tensile splitting method.

Test results are shown in Table 8 and Figures 4 to 11. The results of the 28 day field and laboratory flexural and tensile testing are compared in Table 9.

The 30 MPa field concrete flexured and split tensile test results show that the test mix strengths were 10% less than that of the equivalent control concrete strength at 28 days, however the laboratory split tensile test results showed similar averages for the 35 MPa concrete for the 100% NPC, for the 75% NPC, 25% Slag and for the 50% NPC, 50% Slag at 28 days, whilst the 30 MPa concrete results showed some minor variation in the test results.

C. Test Materials

The materials used in both the field and laboratory test programs are shown in Table 1.

Portland cement Type 10 for the field program was supplied by the Canada Cement Lafarge Co. Woodstock plant, and this was also used in the laboratory program in conjunction with the St. Marys Cement Co. Type 10 cement from the Bowmanville plant. The physical and chemical properties of the Portland cement are shown in Tables 3 and 4.

Slag was supplied to both the field and laboratory test programs by the Standard Slag Cement Co., Fruitland plant. The sieve analysis of the Slag is shown in Table 2 and the chemical analysis in Table 3.

Concrete coarse and fine aggregates were both supplied by J. F. Marshall and Sons Ltd., London for both the field trial and laboratory test programs. The physical properties of the aggregates are shown in Table 5. The aggregates met MTC requirements.

The Master Builders Co. Ltd. MBL 83 Type WN water reducing admixture was used in both the field trial and laboratory test programs and their MBHC Type R set retarding admixture in the laboratory test program.

The Master Builders Co. Ltd. MBAE 10, air entraining agent was used in both the field trial and laboratory test programs.

D. Mix Proportions

The two 30 MPa concrete mix designs used in the field trials are shown in Table 6.

The mix designs shown in Table 6 are similar, except that the test mix has 35 kg less sand and 35 kg more stone than the control mix.

D. Mix Proportions (cont'd)

This adjustment in aggregate proportions was made on the advice of the Standard Slag Cement Co., in order to gain optimum strength proportions in the Slag concrete. The reduced fine aggregate content of the test concrete is also due partly to the mix proportioning procedures that takes into account the difference in specific gravity of the Slag and portland cement.

Also the test mix had 3 kg less water and therefore a slightly lower water/cement ratio than the control.

The twenty-four 30 and 35 MPa concrete batches used in the laboratory trial program are described in Table 8.

E. Test Results and Discussion

Concrete Slump and Air Content Tests

The field trial slump and air content test results are presented and summarized in Table 7. The mean value of the Slag concrete slump test shows an approximate 20 percent increase over the results for the control concrete, and in fact one load of test concrete was rejected at the site because it had an unacceptably high slump.

The Standard Slag Cement Co. manual on the properties and uses of Standard's Slag cement Section III recommends an increase of the air entrainment dosage by 15% when Slag is used. The 75% NPC 25% Slag test mix concrete air entraining admixture MBAE 10 dosage was therefore increased from 45 mL/100 kg NPC in the control mix to 55 mL/100 kg NPC and Slag in the test mix as shown in Table 6. Better control of the entrained air was achieved in the test mix concrete than in the control mix concrete as shown in Table 7. The air entraining admixture dosage rates were not increased for the laboratory Slag test mixes shown in Table 8.

The average air content of the test mix was 10 percent higher than that of the control mix. Both the control and test concrete mixes

were readily pumpable, and the pumping subcontractor described the test concrete as "more easily pumpable". The structural contractor placing the control and test concrete decks could not detect any significant differences in the consolidation or the ease of finishing of the two concretes.

The laboratory test program slump and air content data for the 24 batches of concrete is presented and summarized in Table 8. Excellent control of both slump and air content was achieved, the slump in all batches being controlled between 75 and 90 mm, and the air between 5.5 and 6.5 percent.

Concrete Bleeding Tests

The field trial bleeding test results are presented in Figure 15. Initially the rate of bleeding of the Slag test mix was approximately twice that of the control mix, and due to the longer initial setting time the total bleed water was substantially greater than the control mix. The higher bleeding rate of the test mix was somewhat unexpected since the mix contained a higher air content, and the increased fineness of the Slag material would normally reduce bleeding rates. The high volume of test concrete bleeding may also have been due in part to the use of the admixture at a dosage rate 1.25 times the Ministry's standard for a Type WN product. It appears that the retarding effect on the test concrete was substantially greater than on the control concrete. This increase in bleed water quantity was not, however, observed on the test structure deck during construction. Up to the time of application of the curing compound both the control and test structure decks were observed to have similar, almost negligible, bleeding characteristics.

Time of Setting

The field trial test results are presented in Figure 14.

Tests to measure the time to initial and final set of the field concretes were carried out on samples obtained at the ready mix plant from load 7 of the control mix and load 3 of the test mix. The tests were carried out using a Soiltest Pocket Penetrometer on mortar samples sieved from the concrete.

The 100 percent NPC control mix concrete had a slump of 60 mm, an air content of 5.0 percent, an initial set of 3 1/4 hours, and a final set of 5 3/4 hours.

The 75 percent NPC 25 percent Slag test mix concrete had a slump of 80 mm, an air content of 7.3 percent, an initial set of 6 hours, and a final set of 9 1/4 hours.

The difference in the setting times of the two mixes appears to be due to two reasons, they are:

i) the difference in slumps of the two loads tested, and to a lesser degree, to the difference in air contents of these two loads

ii) the lignin type admixture appears to have a more drastic retarding effect on the test concrete than on the control concrete.

Heat of Hydration

Samples of Slag delivered to the Red-D-Mix concrete plant in Strathroy during the placement of the test structure deck were obtained and combined into one sample. This sample, together with a sample of the NPC Type 10 cement delivered to Strathroy during the course of the field test program was delivered to the Ontario Research Foundation laboratory in Mississauga for heat of hydration testing.

The testing to compare the heats of hydration of the control 100 percent NPC, the 75 percent NPC 25 percent Slag, and the 50 percent Slag test mixes was performed in accordance with the requirements of ASTM C-186. The results of the testing are shown in Table 12. The tests indicate that the 75 percent NPC 25 percent Slag sample meets the CSA Standard CAN3-A5-M77 for a Type 20 Moderate Portland Cement (maximum allowable 300 kJ/kg) and the 50 percent NPC, 50 percent Slag sample meets the CSA Standard CAN3-A5-M77 for a Type 40 Low Heat of Hydration Portland Cement (maximum allowed 275 kJ/kg).

Concrete Strength Tests

The field trial test results are presented and summarized in Table 7 and Figure 3 (commpressive strength tests) and Table 9 (fexural and tensile strength tests).

The standard deviation, coefficient of variation and mean strengths of the 28 day compressive strength tests indicate no significant difference between the test concrete (containing the Slag) and the control concrete. The concrete in both deck slabs complied with the requirements of the strength specification for the 30 MPa class and can be classified as excellent (7) in terms of production control.

The theoretical standard distribution curves shown in Figure 5 indicate that at 28 days the field concrete in both the control and the test mix meets the 30 MPa job requirement.

The MTC minimum compressive strength test acceptance requirements as detailed in Form 1350.08.02 are as follows:

i) The average of all groups of three consecutive strength tests shall be equal to or greater than the specified strength.

ii) No individual strength test shall be more than 3.5 MPa below the specified strength.

and the specification also notes that: the strength criteria can be expected to be met if the concrete is proportioned to produce an average strength as follows:

a) 1.4 times the standard deviation above the specified strength when the standard deviation is less than 3.5 MPa.

b) 6.0 MPa above the specified strength when the standard deviation is between 3.5 MPA and 4.0 MPa.

c) At least 8.0 MPa above the specified strength when the standard deviation exceeds 4.0 MPa or is not known.

The standard deviation of the control 100 percent NPC mix was 2.26 MPa and achieved an average strength of 36.8 MPa. The standard deviation of the test 75 percent NPC 25 percent Slag mix was 1.82 MPa and achieved an average strength of 35.5 MPa.

Both the control and test mixes met the MTC requirements, however, the test mix appears to be somewhat more uniform, with less variation in the mass, which indicates better overall quality concrete.

The field trial tests for flexural and tensile strengths indicated approximately 10 percent lower values for the test concrete than the control concrete. Factors contributing to this difference in strength included an approximately 10 percent higher air content and a 20 percent higher slump in the test concrete than in the control concrete.

The results of the laboratory test program are presented and summarized in Table 8 and Figures 4 to 11. In general, the replacement of portland cement with Slag slows down the rate of strength development at early ages, but is slightly beneficial to concrete compressive strength at 28 days and later. Considering the average strengths of the mixes with two sources of portland cement and two types of chemical admixture in the two classes of concrete, replacing 25 percent portland cement with Slag had the effect of reducing three day strengths substantially (17 percent) and seven day strengths slightly (7 percent). Increasing the Slag content to 50 percent of total cementitious material further reduced early strengths - 43 percent less than the control concrete at three days and 22 percent at seven days. Slag increased slightly 28 and 90 day strengths (2 to 5 percent).

Neither the source of cement or the type of chemical admixture appeared to significantly affect the magnitude of this early concrete strength reduction with the addition of Slag.

The 28 day tensile tests in the laboratory program indicated a slight increase (5 to 7 percent) when comparing the Slag mix to the control mix.

At constant slump and air content replacing portland cement with Slag did not significantly affect the water requirements of the laboratory concrete mixes.

Pulse Velocity Tests

Before testing the field trial 7, 14, 28 and 90 day concrete cylinders in compression, the specimens were evaluated for pulse velocity characteristics.

Pulse velocity measurements were made using a total of 12 cylinders from each of the two loads of ready mixed concrete designated for special testing, that is from the control load 7 and the test load 3.

The pulse velocity path length was 304 mm. The time of travel of the pulse on each cylinder was measured three times, and the average transit time was recorded in km/sec. The results are shown in Table 11.

The initial strength of the test concrete at 7 days is 25% lower than that of the control mix, as the test concrete initially develops strength at a slower rate, however the data shows that at 14 days and at later ages the rate of strength development in both the test and control mixes appear to be similar. At all ages tested the compressive strength of the test, 75% NPC 25% Slag concrete is shown to be significantly lower than that of the 100% NPC control mix.

Scaling Resistance to Deicing Chemicals

The results of the scaling resistance testing of the field slabs of control and test concrete are shown in Figures 12 and 13. Two 75 x 300 x 300 mm slabs of concrete were cast from the control load 7 at the structure site and two from test load 3. The slabs then received a brushed finish and were cured with wet burlap overnight before they were shipped to the MTC Downsview laboratory, where each was fitted with a water retaining dike to its upper perimeter.

The salt scaling slabs were moist cured for 14 days and for a further 14 days in the laboratory and then tested in accordance with ASTM C672-76 with the following exceptions. The deicer was a three percent sodium chloride solution. The scaling was evaluated after each five cycles by determining the dry mass of the scaled material per unit area of the surface exposed to scaling (kg/m^2). Each slab was submitted to one freezing and thawing cycle per day for fifty cycles. The scaling resistance of the slabs to deicing chemicals was evaluated by determining the accumulated dry mass of the scaled material from each slab. Figure 12 shows the test results and Figure 13 the appearance of one control and one test concrete slab before and after completion of the fifty freeze thaw testing cycles. The Ministry guideline for concrete acceptance is a maximum cumulative surface loss of 0.8 kg/m^2. The control concrete averaged 0.25 kg/m^2 and the test concrete 0.21 kg/m^2. The test results from both concretes are essentially equal, and they are well within MTC performance criteria for durable concrete.

Parameters of the Air Void System in the Hardened Concrete

The air contents of the field control and test plastic concretes measured at the structure sites are presented and summarized in Table 7. Table 10 compares the air contents of four loads of the plastic control concrete and three of the test concrete with their air void parameters in the hardened concrete. The cores were sliced vertically in half and linear traverse testing was performed through the depth of the cores.

Table 7 shows that the air content of all the control and test concrete delivered to the sites of the structure met MTC requirements (Form 1350.05.02, Table 2 requires the air content of the plastic concrete to be 6 percent ± 1.5 percent).

Table 10 shows that the air content of the hardened concrete as determined by linear traverse testing in five out of seven cases is less than the air contents of the plastic concretes at these locations. These five lower air contents in the hardened concrete

indicate that air content is lost in the pumping, placing and finishing processes of concrete construction. In the two cases where in the control concrete the air contents are marginally higher in the hardened concrete, this may indicate some lack of uniformity in the air contents of the concretes delivered in these loads.

In general the differences in measured air content between the plastic concrete and the hardened concrete for both the control and test mixes are considered normal for this type of construction.

Table 10 summarizes the data on the specific surface, voids/mm, and the spacing factor characteristics of the control and test concretes.

The specific surface of the air voids indicates the average size of the bubbles. The higher the specific surface the smaller the bubbles. The results of the specific surface determinations for all four control concrete samples are slightly below the generally accepted minimum desirable figure (25.0 mm^{-1}), however, the results for two out of three of the test concrete samples are above the minimum requirements.

The spacing factor is the average distance from any point in the cement paste to the periphery of the nearest air bubble. For good resistance to freezing and thawing the spacing factor should be 0.20 mm maximum. The spacing factor parameter for specimens representing both the control and test concretes are satisfactory.

Appearance of Deck Slabs

The two Sydenham River structures that formed the field trial were inspected in May 1981, after one year's exposure to field freeze-thaw conditions. The structure decks were not open to traffic and the concrete had not been waterproofed and paved with asphalt. No sodium chloride had been applied to the concrete surfaces. Both structure decks were in excellent condition. No shrinkage cracking was visible on either deck. The test structure exhibited an unusual

surface appearance phenomena (Fig. 19) which did not appear on the control structure deck. This phenomena took the form of a random loss of a thin surface layer of paste probably caused by the effects of winter exposure conditions and by the increased bleeding rate and longer bleeding period of the test concrete compared to those of the control concrete. When the two structures were reinspected in June 1982, the surface layer phenomena on the test structure deck was much less aparent than it had been in May 1981.

7. CONCLUSIONS

The results of the testing and evaluation described in this paper lead to the following conclusions:

i) the field trial concrete in both deck slabs complied with the requirements of the strength specification for 30 MPa class concrete and the production control of both concretes was excellent. At 28 days compression strengths were essentially equal. Field trial flexural and tensile tests indicated approximately 10 percent lower values for the test concrete compared with the control concrete.

ii) the laboratory trial program showed that the replacement of portland cement with Slag slowed the rate of strength development at early ages, but at 28 days and beyond the Slag is slightly beneficial to compressive strength. At 25 percent replacement of NPC with Slag, 3 and 7 day compressive strengths were reduced by 17 percent and 7 percent respectively. Neither the source of cement or the chemical admixture appeared to affect the strength of the concrete in the laboratory experiments. At constant air and slump replacing NPC with Slag in the laboratory experiments did not significantly affect concrete mix water requirements.

iii) the scaling resistance to deicing chemicals of the test and control concretes was well within generally recognized performance criteria for durable concrete.

iv) the linear traverse testing of the air void parameters of the hardened concrete from the field made specimens indicated in general a satisfactory air void system in the control and test concretes.

v) the setting times and bleeding characteristics of the field trial test mix concrete were substantially greater than the control concrete.

vi) the heat of hydration testing showed that when replacing 25 percent NPC with Slag, the composite sample meets the CSA Standard for a Type 20 Moderate Portland Cement, and with a 50 percent replacement it meets the CSA Standard for a Type 40 Low Heat of Hydration Portland Cement.

8. RECOMMENDATIONS

This report recommends that:

i) The use of Slag be permitted in all Ministry structural and pavement concrete work as a partial replacement for portland cement.

ii) Initially the proportions of cementitious materials be three parts portland cement and one part Slag, by mass.

iii) The use of Slag be at the option of the contractor. It is necessary to make contractors and suppliers aware of the reduction in early concrete strength when portland cement is partly replaced by Slag.

iv) Additional work be carried out to investigate:

- The strength gain of Slag under cold weather conditions
- The bleeding and setting time characteristics of Slag when used in conjuntion with various commonly used chemical admixtures
- The optimum mix proportions and Slag/portland cement ratio for Ministry work.

9.

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6. Mills, R.H., "Assay of Blast Furnace Slag as Cement", Proceedings, 5th International Symposium on Concrete Technology, Monterrey, Mexico, March, 1981, pp. 84-116

7. ACI Standard 214-77, "Recommended Practice for Evaluation of Strength Test Results of Concrete", American Concrete Institute, Detroit, Michigan, 1977

Acknowledgements

The author would like to acknowledge the assistance of the Standard Slag Cement Company and of the Red-D-Mix Concrete Company who supplied samples and testing facilities, to the Trow Group Ltd. who carried out the bleeding, the time of setting, and the flexural beam testing, to the Ontario Research Foundation who carried out the heat of hydration testing, and to the MTC construction and laboratory staff in Southwest Region and the Downsview laboratory staff for the many tests they performed.

Figure 1
Location of Field Test

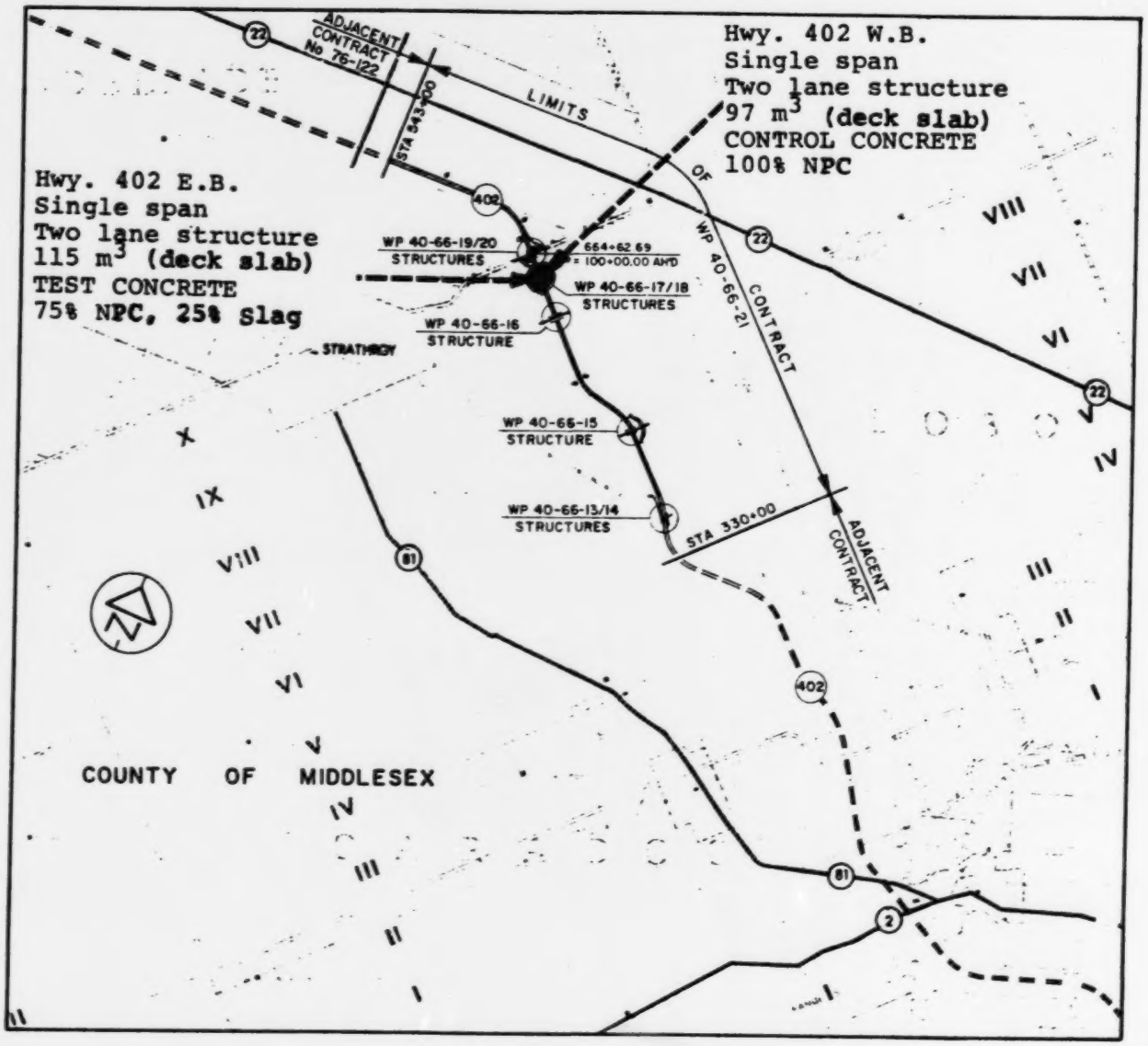
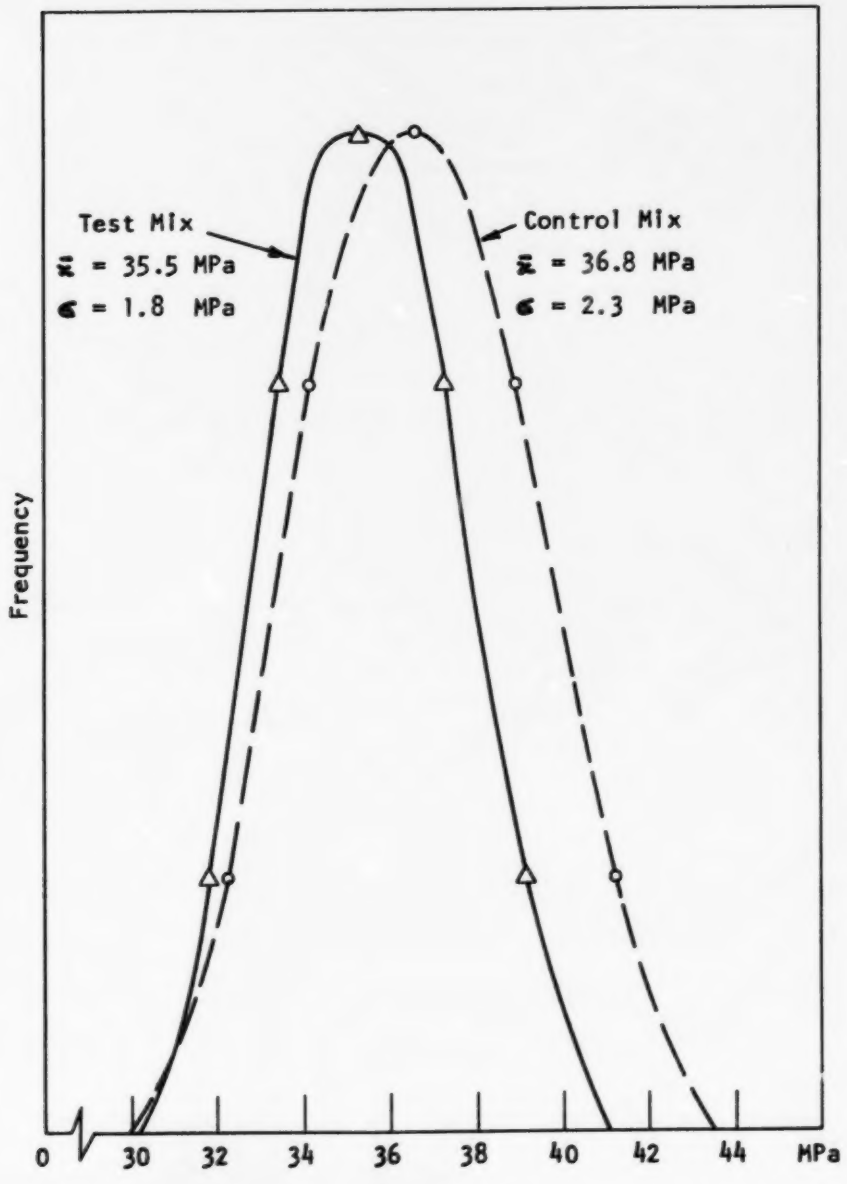


Fig. 2

Photograph of westbound Hwy. 402 Sydenham River Structure Under Construction

FIGURE 3

STANDARD DISTRIBUTION CURVE
28 DAY COMPRESSIVE STRENGTH TESTS (FIELD)



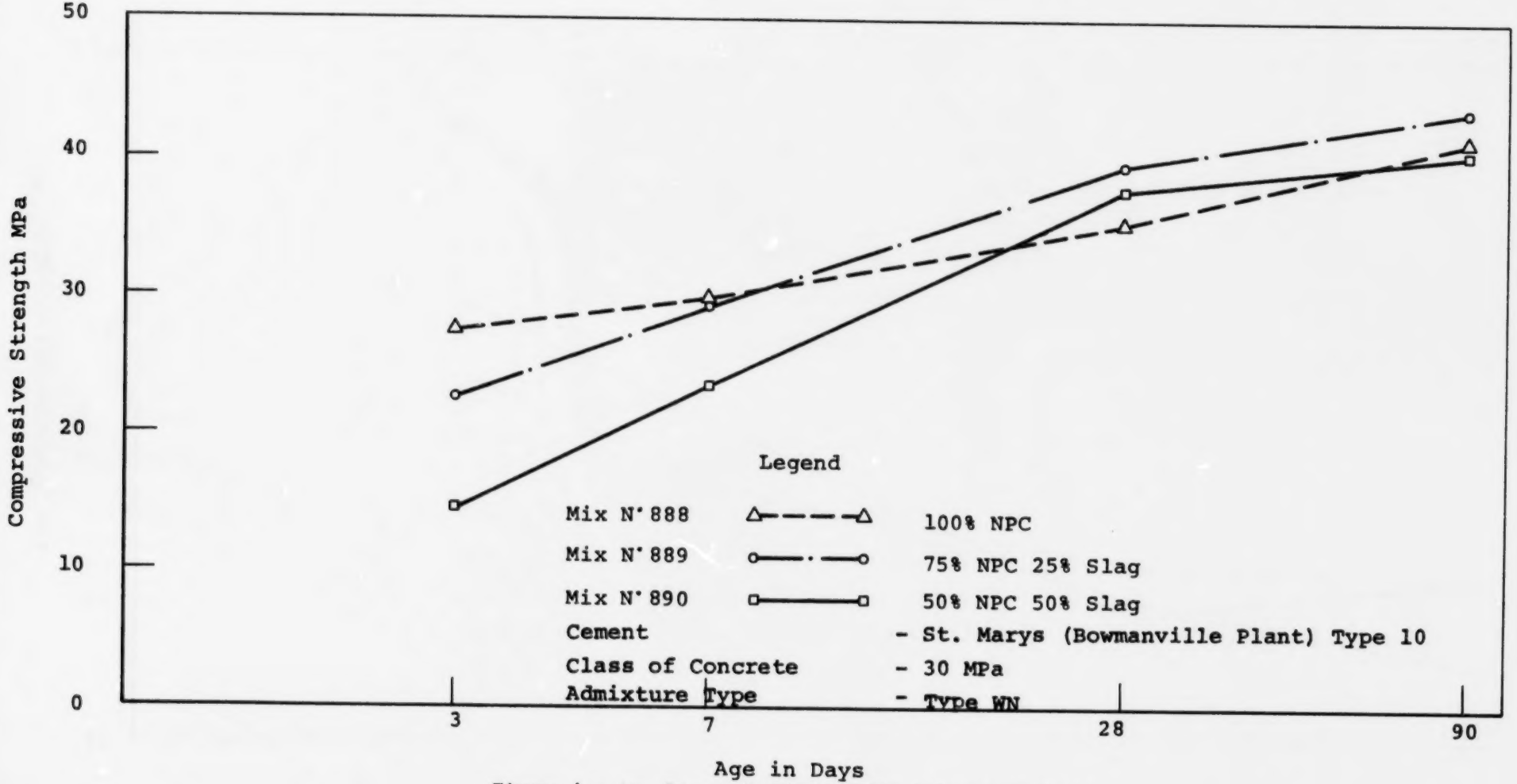


Figure 4 - Age Strength Relationship Laboratory Tests

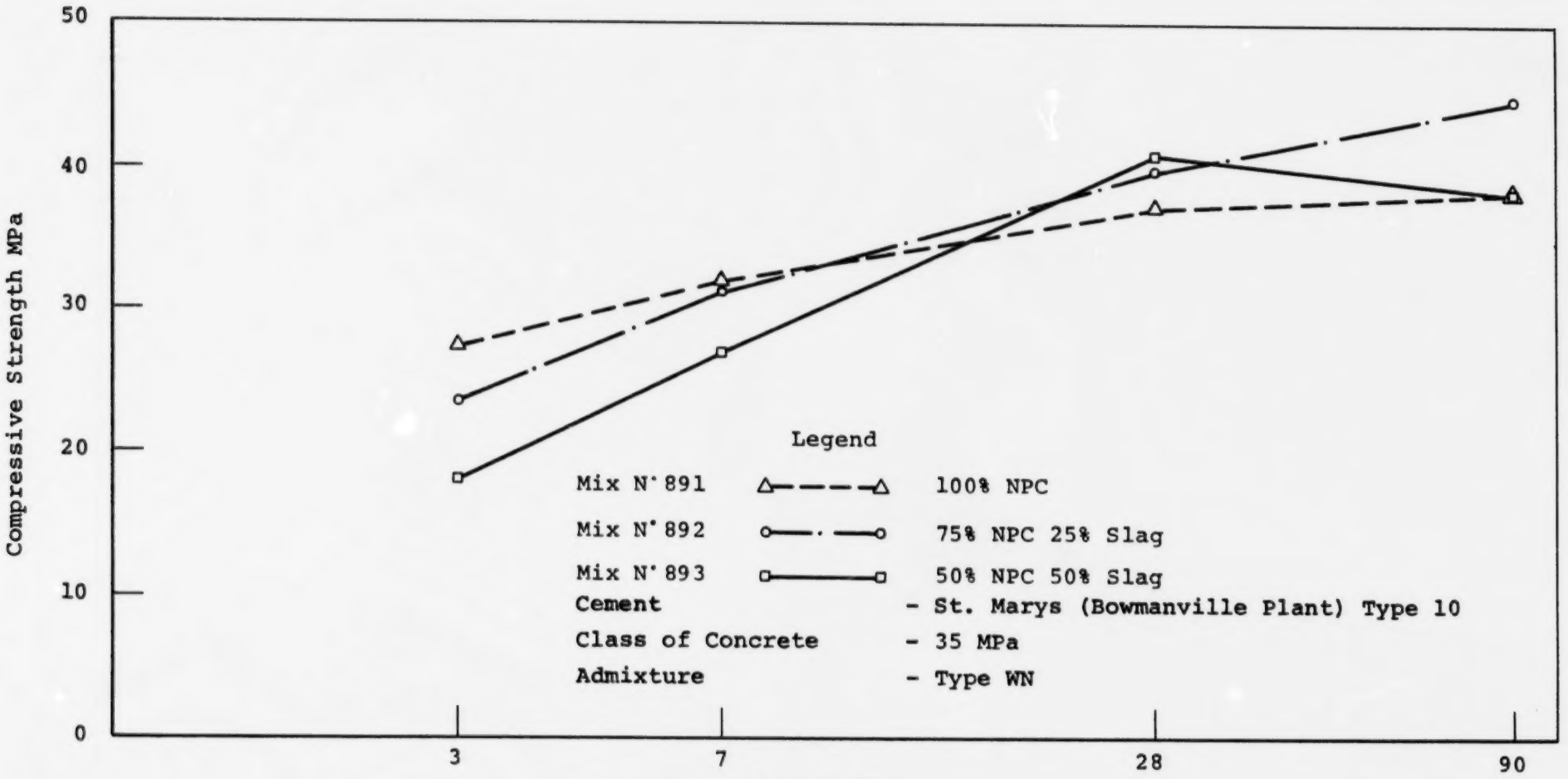


Figure 5 - Age Strength Relationship Laboratory Tests

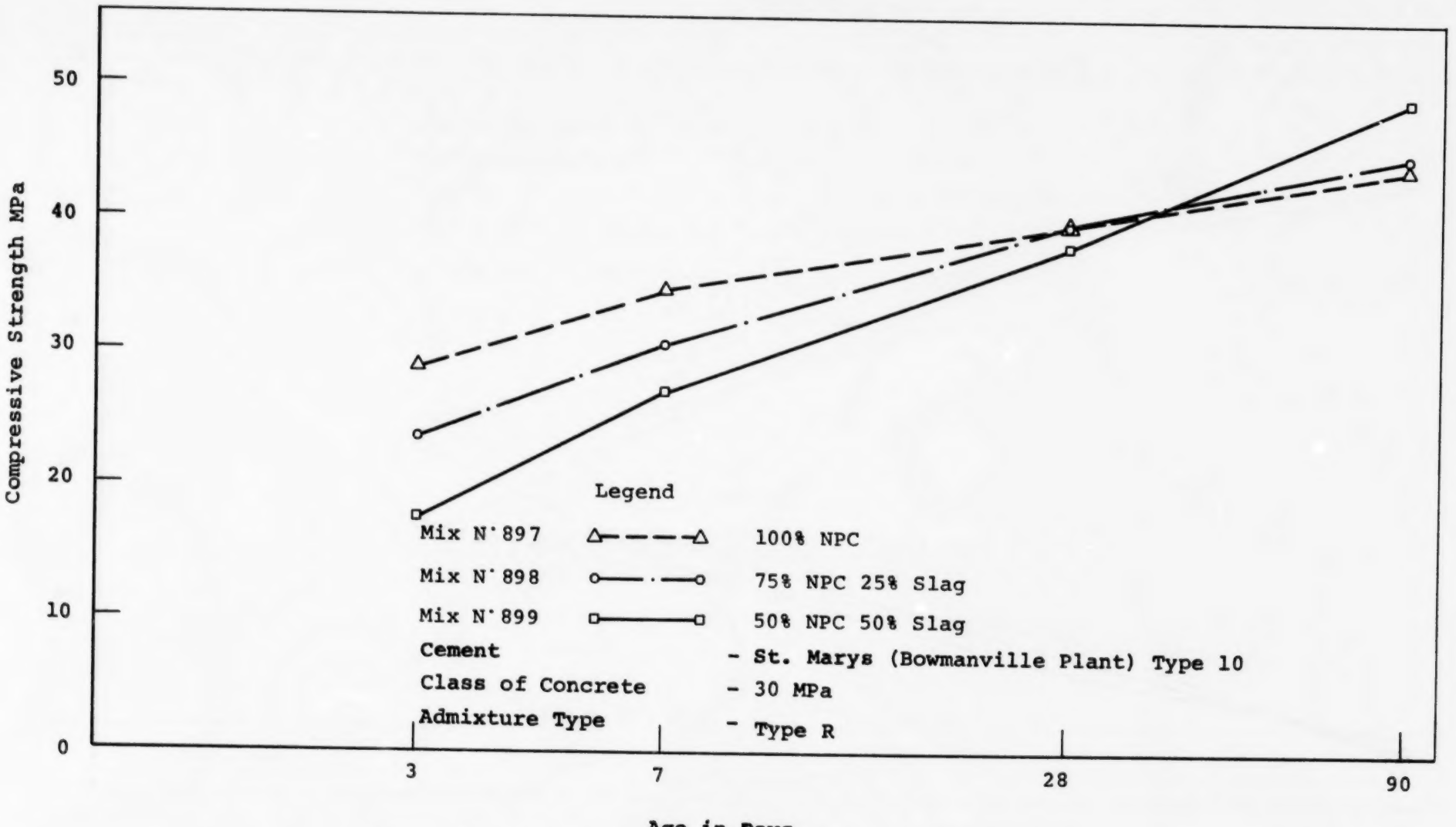


Figure 6 - Age Strength Relationship Laboratory Tests

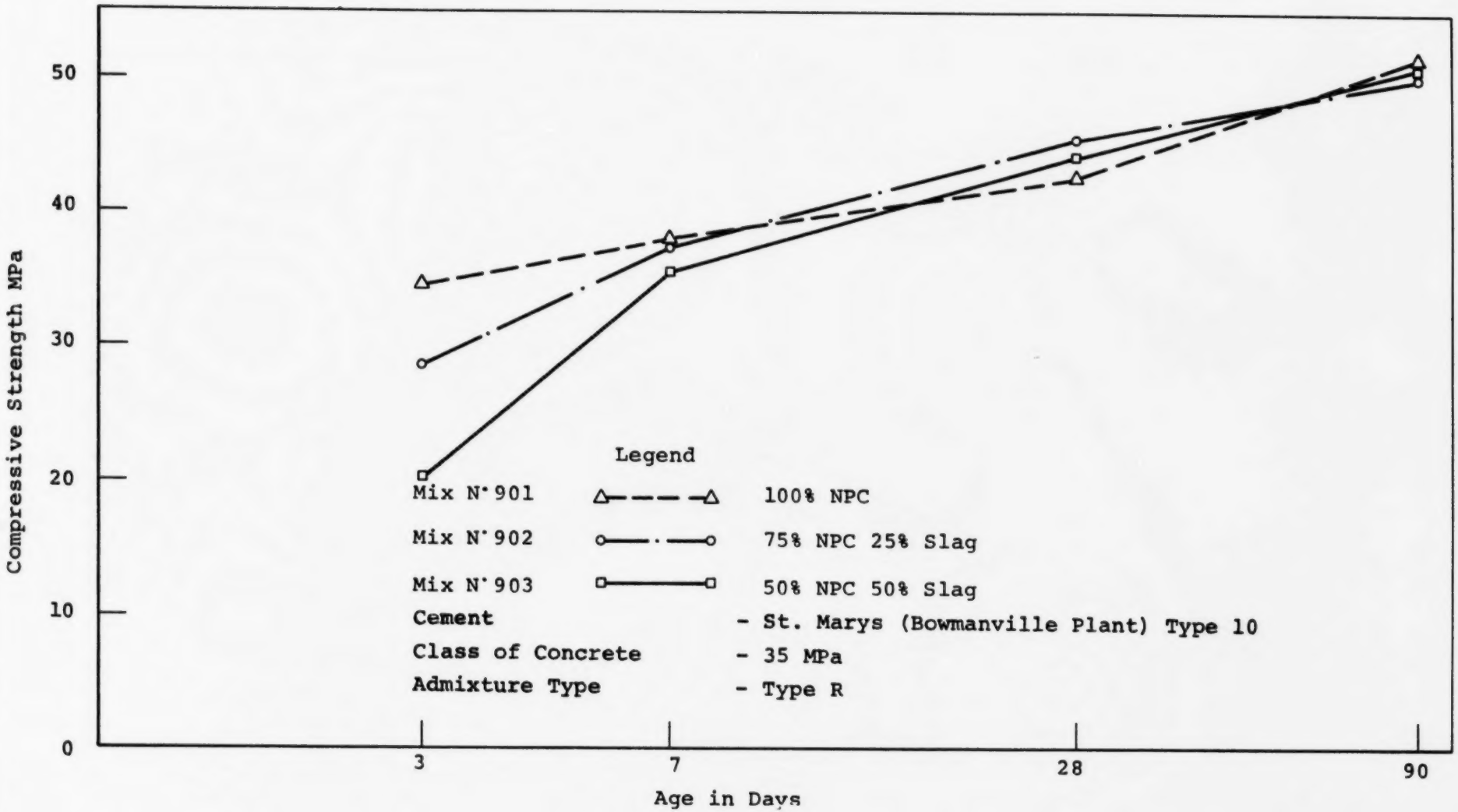


Figure 7 - Age Strength Relationship Laboratory Tests

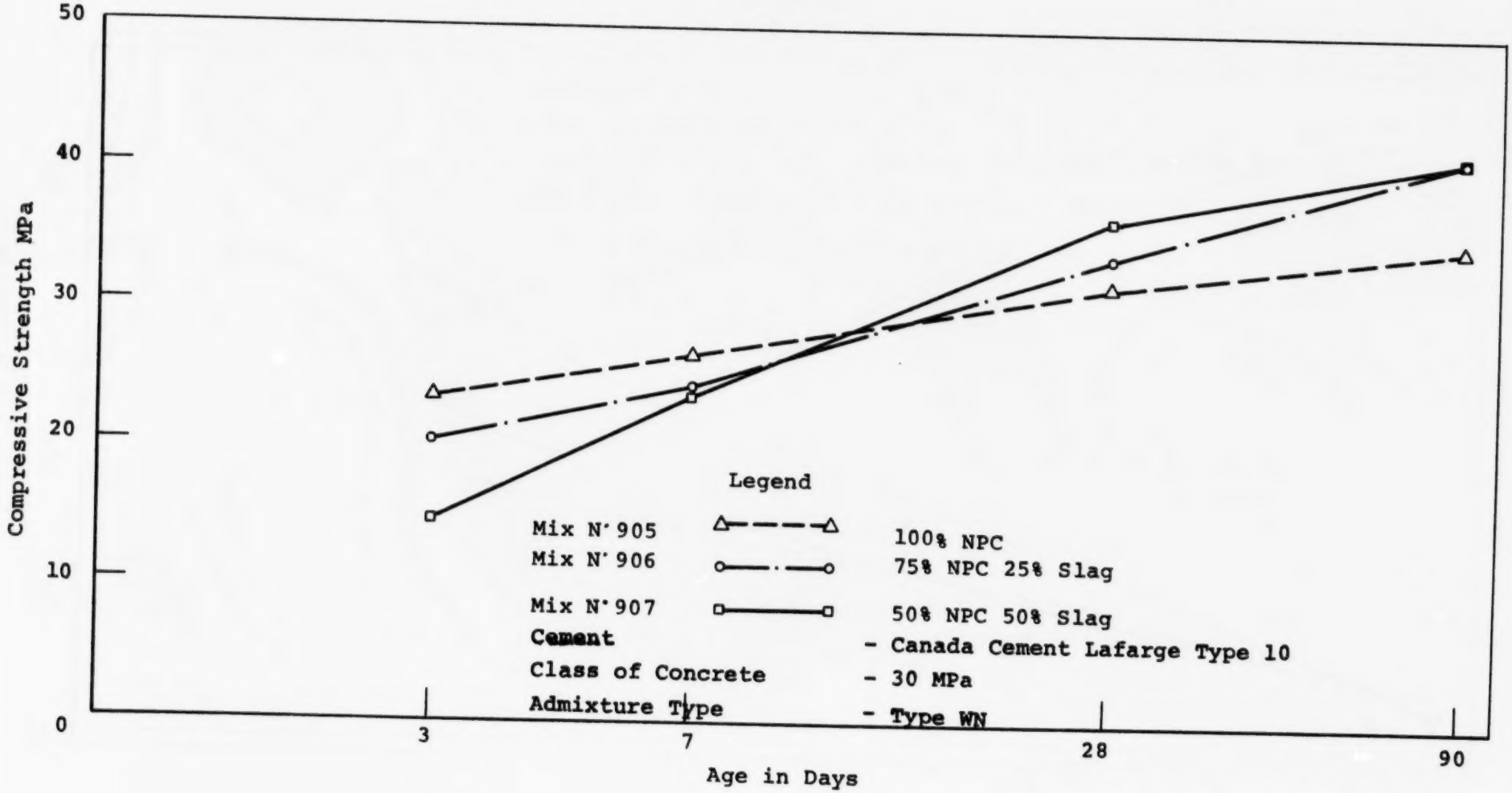


Figure 8 - Age Strength Relationship Laboratory Tests

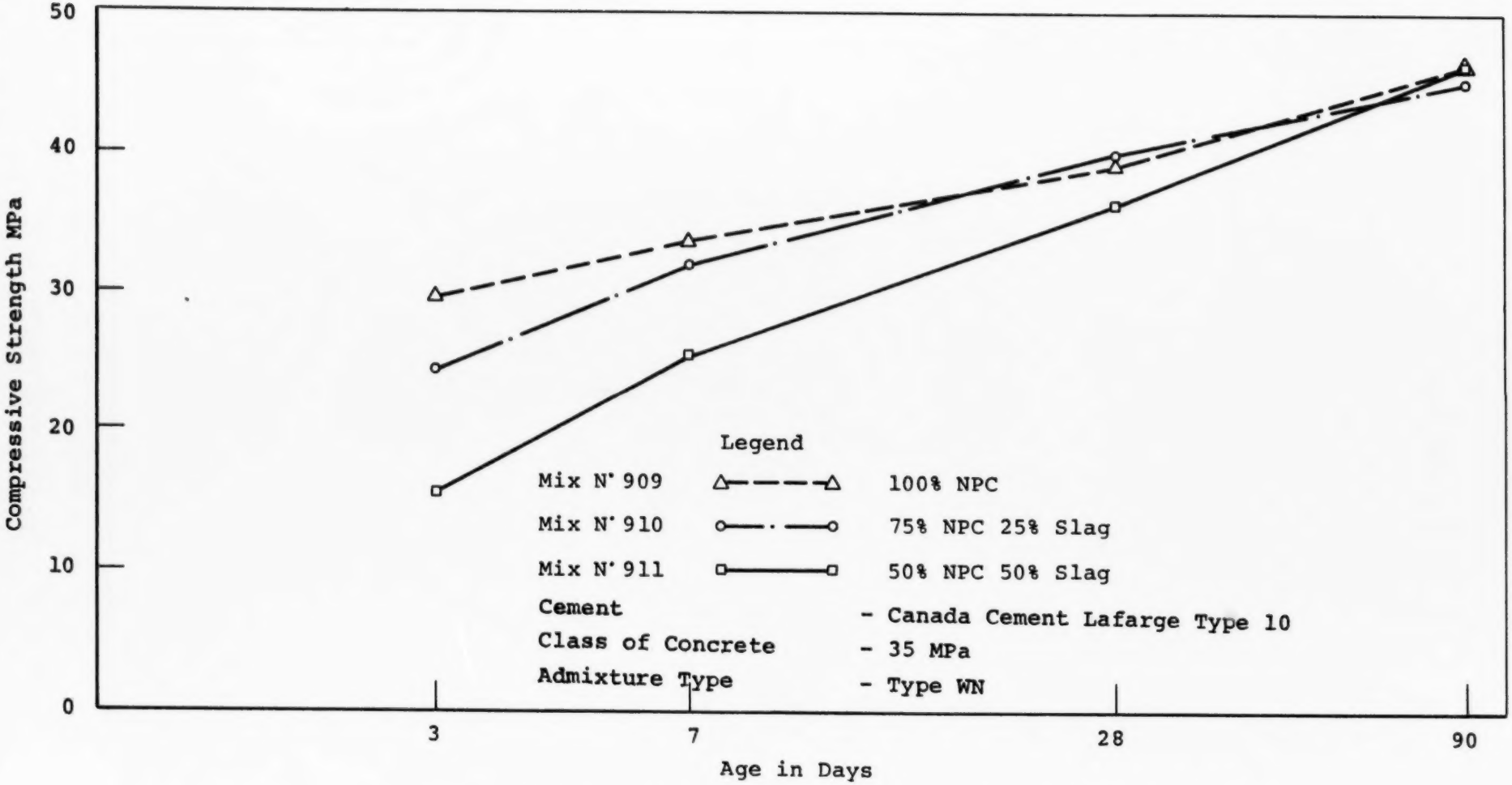


Figure 9 - Age Strength Relationship Laboratory Tests

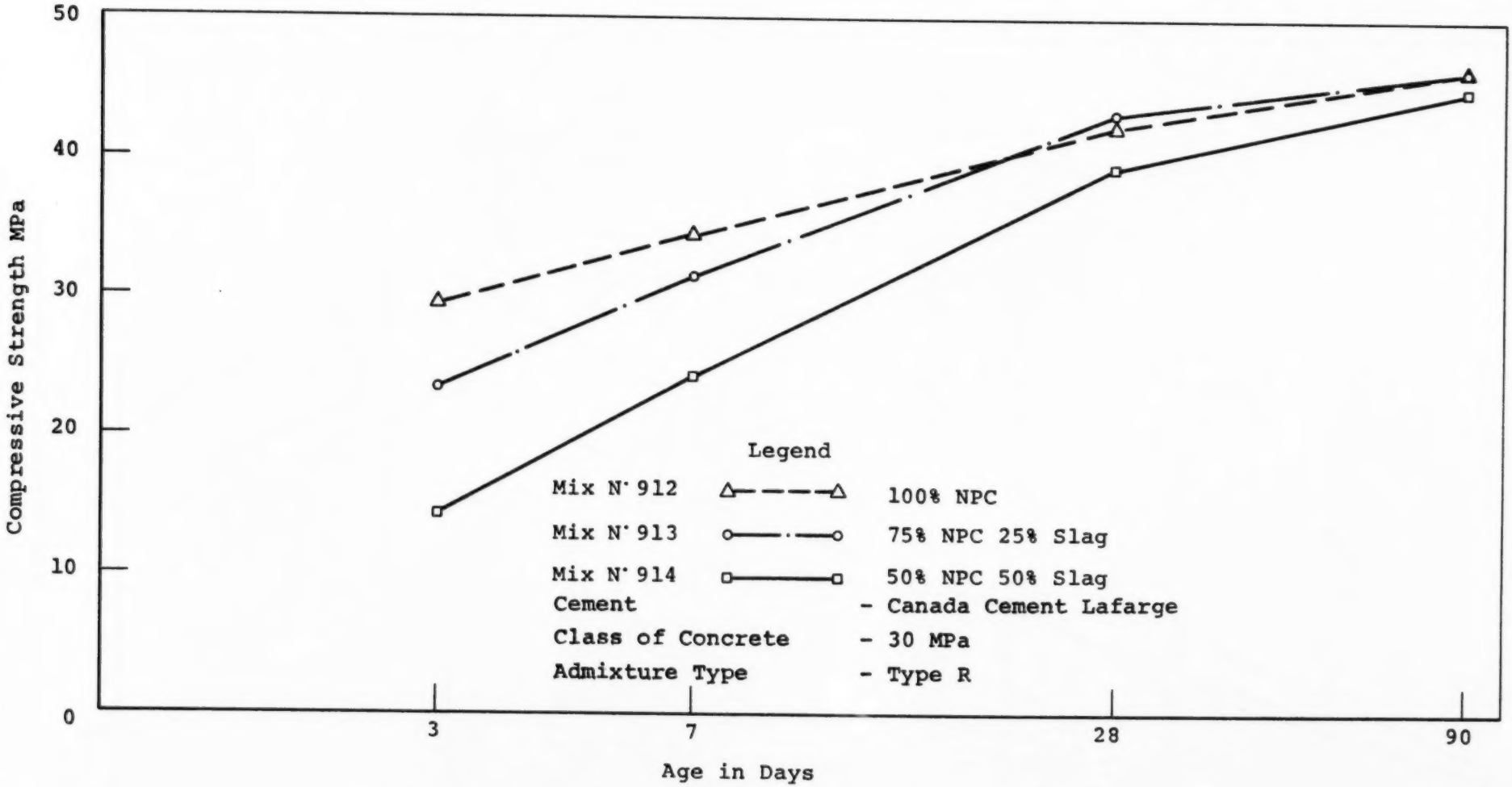


Figure 10 - Age Strength Relationship Laboratory Tests

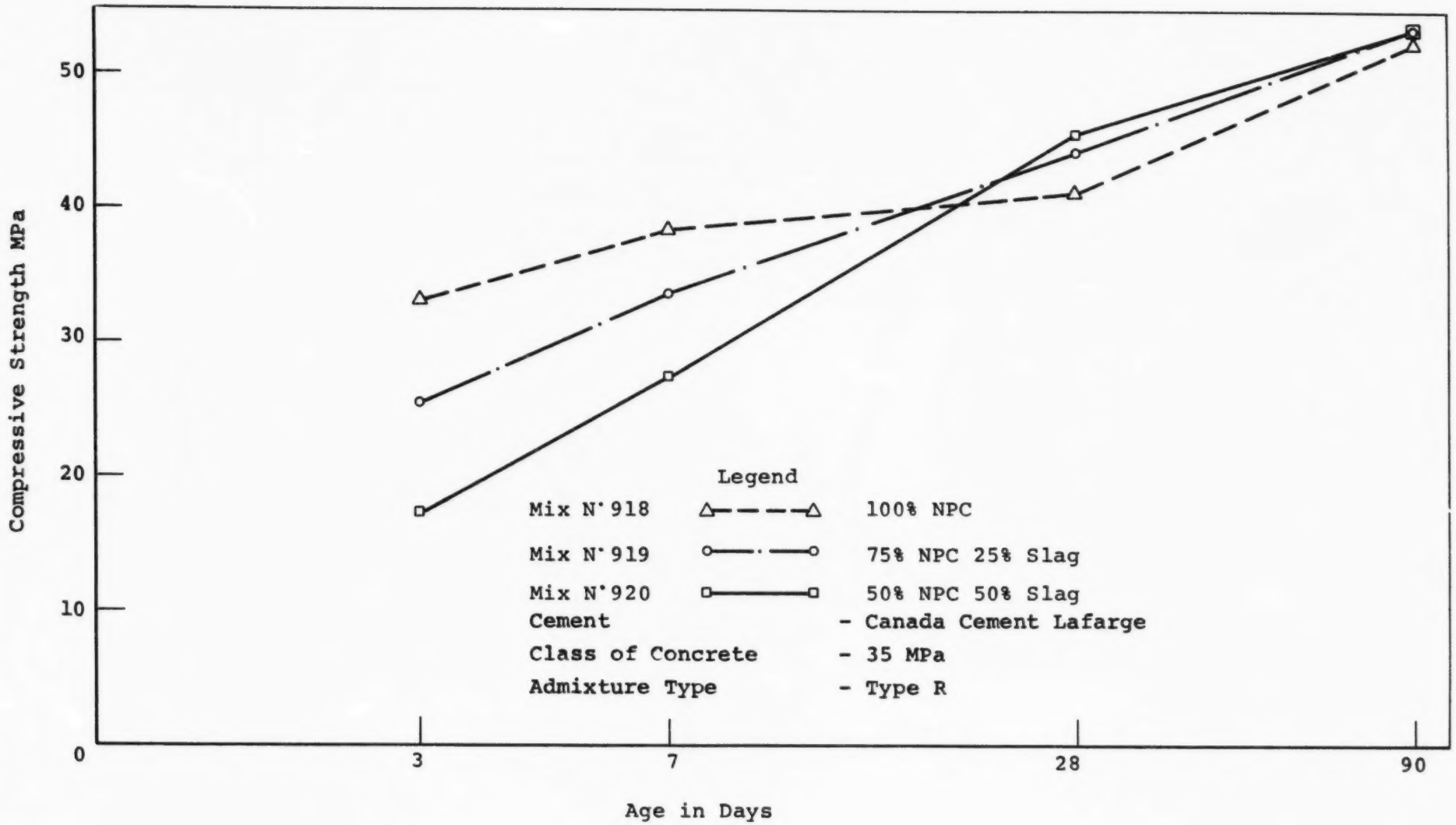


Figure 11 - Age Strength Relationship Laboratory Tests

Figure 12 SCALING RESISTANCE TO DEICING CHEMICALS (FIELD)

△ Test Slabs 1 and 2 100% NPC } CONTROL CONCRETE
Air 5.0% Slump 60 mm

○ Test Slabs 3 and 4 75% NPC, 25% Slag } TEST CONCRETE
Air 7.3 % Slump 80 mm

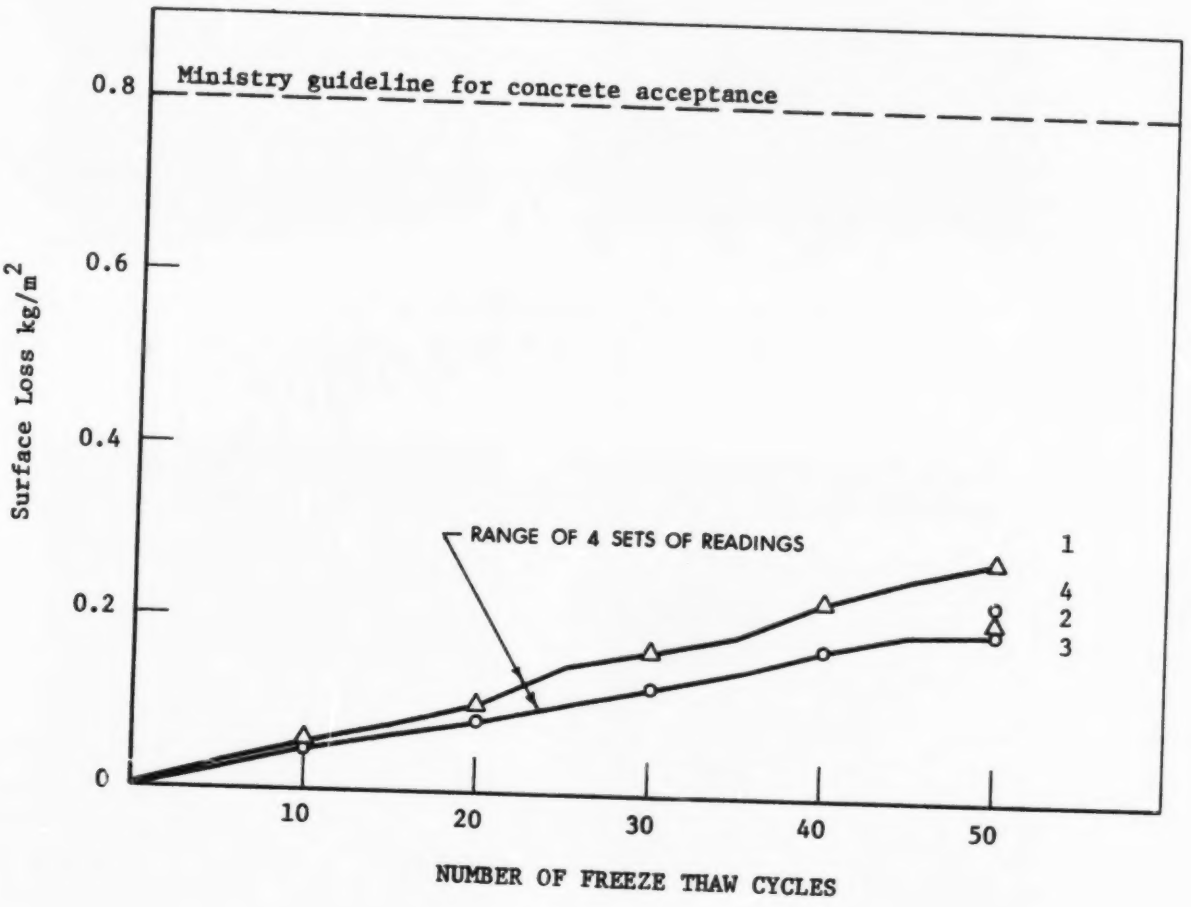
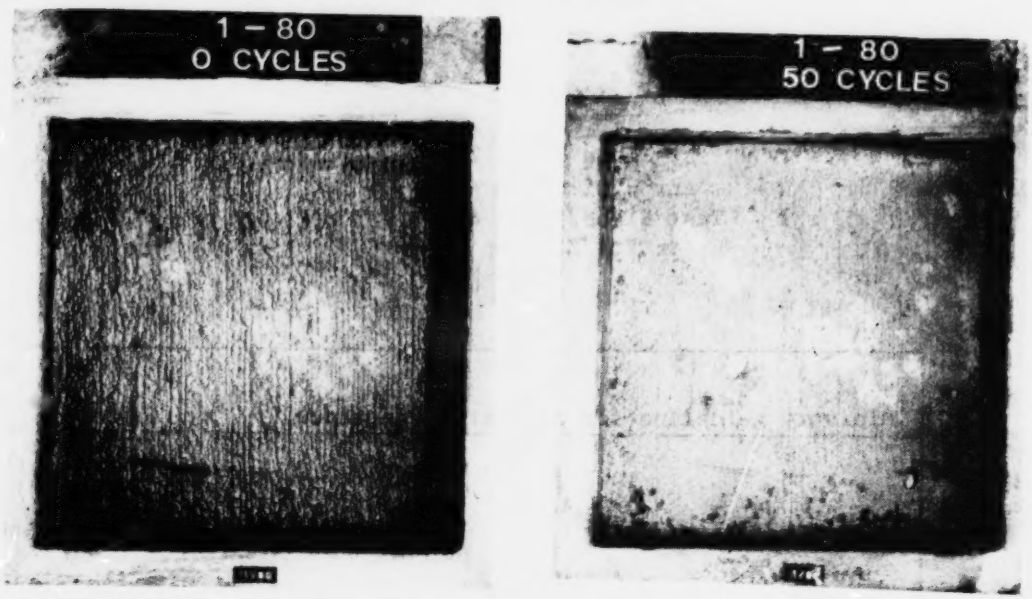
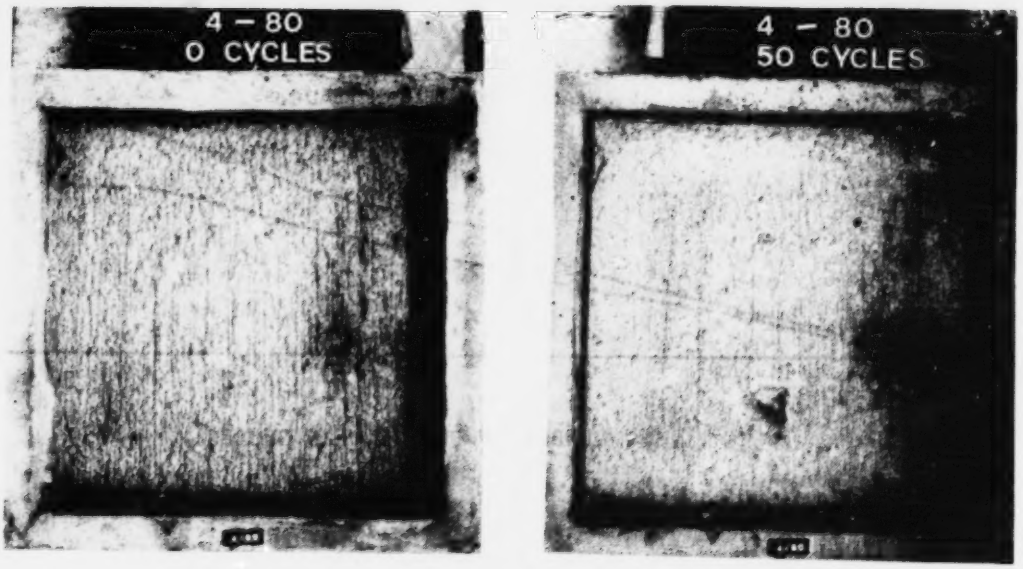


Figure 13

APPEARANCE OF SALT SCALING TEST SLABS
BEFORE AND AFTER EXPOSURE TO 50 FREEZE THAW CYCLES
30 MPa FIELD CONCRETE



Control Concrete 100% NPC



Test Concrete 75% NPC, 25% Slag

Figure 14

Field Concrete Setting Times
Proctor Penetration Test ASTM C-403

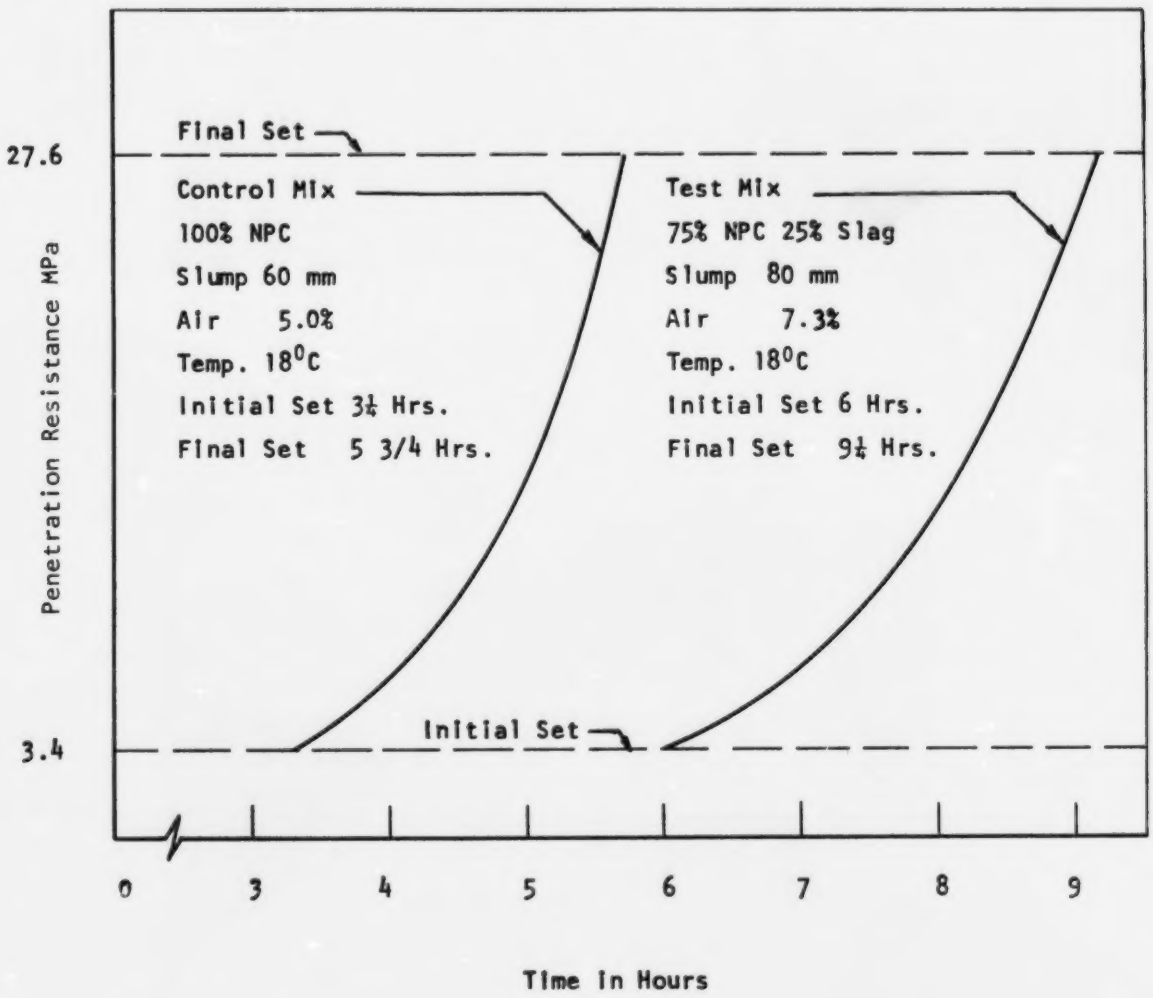
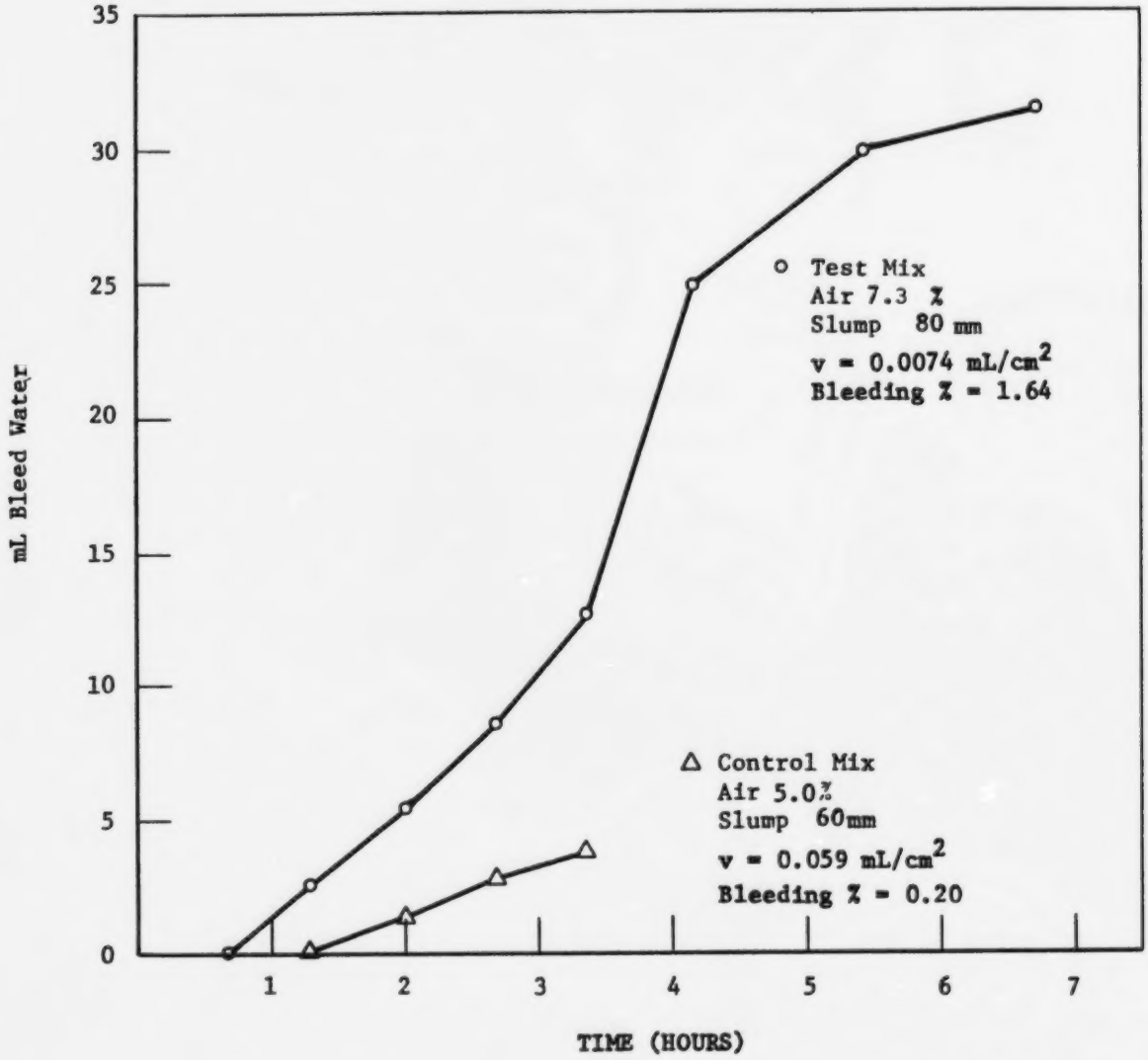


Figure 15
BLEEDING CHARACTERISTICS OF CONCRETE
ASTM C-597



V = Volume of bleeding water per unit area of surface

$$\text{Bleeding \%} = \frac{\text{weight of bleeding water}}{\text{weight of water in the test specimen}} \times 100$$

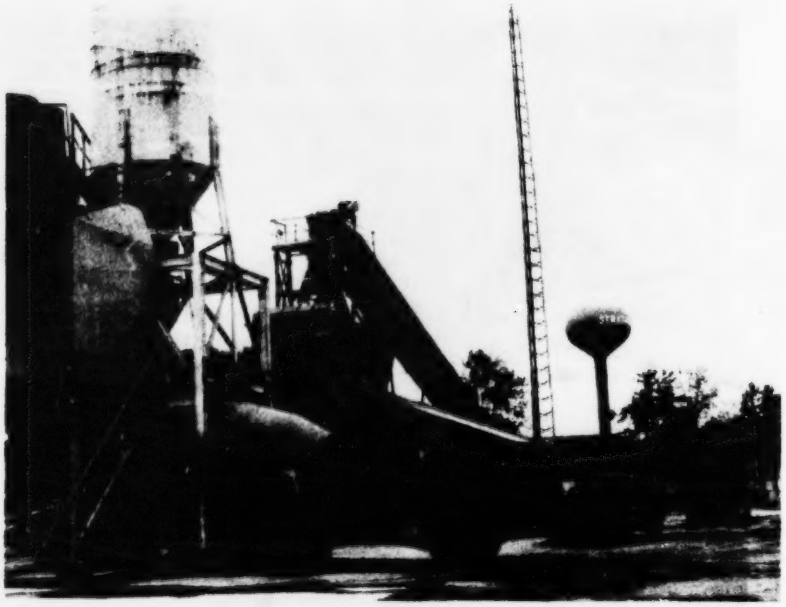


Figure 16
Red D Mix Concrete Batching Plant, Strathroy

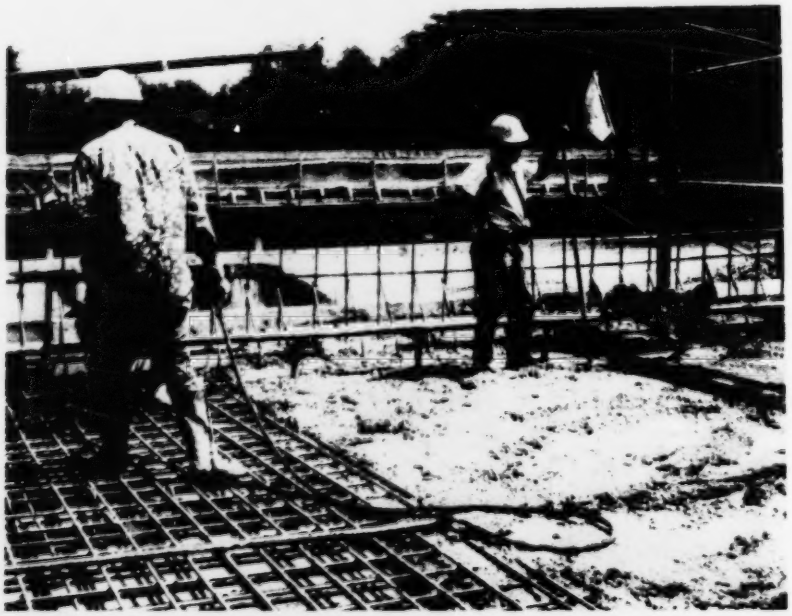


Figure 17
Placing Concrete Ahead of Finishing Machine, Test Mix

Figure 18
Finishing Concrete With Bidwell Machine

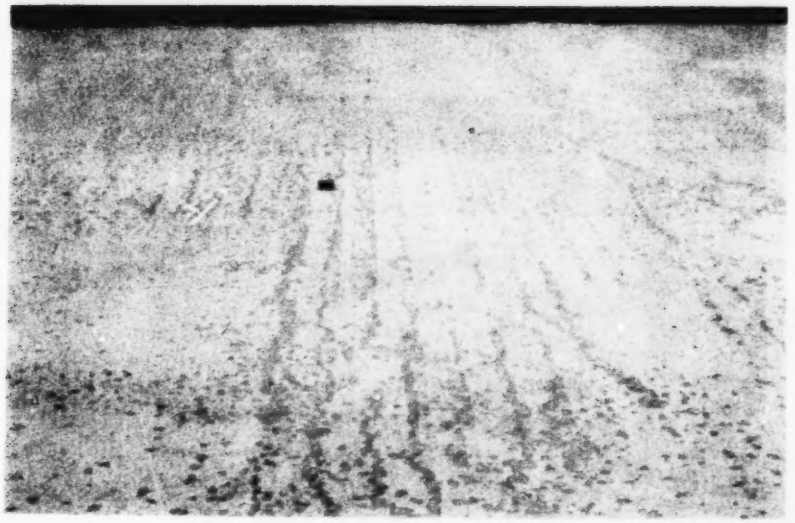


Figure 19
Photograph of the Sydenham River
Test Structure Bridge Deck Showing
"Appearance Phenomena", May, 1981

TABLE 1 TEST MATERIALS

Material	Field Trial	Laboratory Tests	Physical and Chemical Properties Table
Portland Cement Type 10	Canada Cement Lafarge Woodstock Plant	Canada Cement Lafarge Woodstock Plant St. Marys, Bowmanville Plant	3 and 4
Slag	Standard Slag Cement Company	Standard Slag Cement Company	2, 3 and 4
Concrete Coarse Aggregate	J.F. Marshall and Sons Ltd. London	J.F. Marshall and Sons Ltd. London	5
Concrete Fine Aggregate	J.F. Marshall and Sons Ltd. London	J.F. Marshall and Sons Ltd. London	5
Water Reducing Admixture	The Master Builders Co. Ltd. MBL 83	The Master Builders Co. Ltd. MBL 83 MB HC	x Type WR Type R & RX
Air Entraining Agent	The Master Builders Co. Ltd. MBAE 10	The Master Builders Co. Ltd. MBAE 10	xx

x Meeting the requirements of CSA CAN3-A266.2-M78 Table 1
xx Meeting the requirements of CSA CAN3-A266.1-M78 Table 1

TABLE 2 SIEVE ANALYSIS OF PELLETIZED GRANULATED BLAST FURNACE SLAG

SIEVE ANALYSIS	
SIEVE ANALYSIS	PERCENT PASSING
13.2 mm	100.0
9.5 mm	100.0
4.75 mm	92.0
2.36 mm	69.0
1.18 mm	33.0
600 µm	17.0
300 µm	10.0
150 µm	6.0
75 µm	4.0

TABLE 3.
CHEMICAL ANALYSIS

RESULTS OF CHEMICAL ANALYSIS % BY MASS

Name of Component	Chemical Formula	Type 10 Portland Cement				Slag			
	Lab. No.	CANADA 80L15 xx	St.MARYS 80L10 xxx	CANADA 80L09 xxx	MTC Form 1301 Requirements	80L18 xx	80L21 xxx	80L27 xx	CSA A363-M77 Requirements
1. Loss on Ignition%		1.01	1.99	1.23	Max.3.0	0.10	0.70	0.40	N.R.
2. Insoluble Residue%		0.10	0.52	0.15	" 0.7	0.36	0.30	0.41	"
3. Tricalcium Aluminate, %	$3CaO\ Al_2O_3$	7.50	10.07	5.91	N.R.	* 0	* 0	* 0	"
4. Sulphur Trioxide%	SO_3	3.20	3.97	2.94	Max 3.5	NIL	0.10	Trace	"
5. Magnesium Oxide %	MgO	3.32	2.70	3.48	" 5.0	8.50	12.92	12.08	"
6. Sodium Oxide %	Na_2O	0.53	0.25	0.50	N.R.	0.21	0.32	0.28	"
7. Potassium Oxide %	K_2O	0.55	0.65	0.44	"	0.34	0.40	0.47	"
8. Alkali Content %	$(Na_2O+0.658K_2O)$	0.89	0.68	0.79	"	0.43	0.58	0.59	"
9. Silicon di Oxide%	SiO_2	21.44	20.80	21.38	"	39.10	39.10	39.32	"
10. Aluminum Oxide %	Al_2O_3	4.53	5.42	3.90	"	10.90	7.76	7.05	"
11. Ferric Oxide %	Fe_2O_3	2.67	2.54	2.62	"	0.80	0.45	0.83	"
12. Calcium Oxide %	CaO	62.75	61.68	63.51	"	37.20	36.95	37.00	"
13. Total Sulphur After Oxidation	S"	-	-	-	"	1.34	1.31	NT	"
14. Oxides Ratio	$\frac{CaO+MgO+Al_2O_3}{SiO_2}$				"	1.48	1.47	1.69	min. 1.0

NOTE :- * The analysis of the tricalcium aluminate % for the slag using the Bogue calculation, - if N.P.C., would be 27.53, 19.80, 17.30.

NT. - Not tested
xx Field samples
xxx Samples submitted for laboratory test program

TABLE 4

PHYSICAL PROPERTIES OF PORTLAND CEMENT AND SLAG

	Type 10 Portland Cement				Slag		
				MTC Form 1301 Requirements	Test Results		CSA A363-M77 Requirements
Lab. No./Batch	xx 80-L-15	xxx 80-L-10/196	xxx 80-L-09/195		xx 80-L-18	80-L-21 xxx	
PROPERTY							
Normal Consistency, %	22.5	24.8	22.3	NR	NT	NT	NR
Rod Penetration, mm	10	10	9	NR	NT	NT	NR
Fineness							
Ret. 75 µm Sieve %	3.6	5.8	4.0	Max. 18.0	NT	NT	NR
Ret. 45 µm Sieve %	NT	NT	NT	NR	14.78	14.52	Max. 20.0
Blaine # cm^2/g	3931	3404	3494	NR	4468	4177	NR
Soundness %	NT	0.034	0.140	Max. 1.0	NT	NT	NR
Setting Time, min.	70	100	75	Min. 45 Max. 360	NT	NT	NR
False Set — Time After Mixing Min.	3 5 8 11 RM	3 5 8 11 RM	3 5 8 11 RM	Min. 25 at 11 min. and Min. 45 after remoulding	NT	NT	NR
False Set — Penetration, mm	50 50 50 50 50	50 50 37 35 50	50 50 50 50 50				
Compressive Strength MPa — 1d	NT	NT	NT	NR	NT	NT	NR
3d	24.4	22.3	19.5	Min. 12.5	NT	NT	NR
7d	30.1	27.8	24.4	Min. 18.0	NT	NT	NR
14d	NT	NT	NT	NR	12.2	12.6	Min. 3.5
28d	36.0	36.8	32.6	Min. 26.5	15.9	15.8	Min. 10.5

Note: NT - Not Tested, NR - No Requirement

1) all tests carried out in accordance with CSA Standard CAN 3-A5-M77 where appropriate
2) false set determined in accordance with ASTM C 359-75
3) field samples
4) samples submitted for laboratory test program

TABLE 5

PHYSICAL PROPERTIES OF AGGREGATES USED
IN BOTH FIELDWORK AND LABORATORY TESTING

		Coarse	Fine
	Sample No.	80-A-12014	80-A-12013
Test			
Los Angeles Abrasion %		22.2	
Mg SO_4 Soundness %		2.5	
Petrographic Number		124.0	
Dry Bulk Relative Density		2.64	2.65
Absorption %		1.00	1.16
Pass 75 µm Sieve		0.8	2.3
Fineness Modulus			2.85
	Sieve Size		
% Retained	19.0 mm	2.9	
	16.0 mm	13.7	
	13.2 mm	28.6	
	9.5 mm	63.4	
	6.7 mm	90.9	
	4.75 mm	98.9	
	6.7 mm		-
	4.75 mm		3.0
	2.36 mm		12.7
	1.18 mm		30.0
	600 µm		60.0
	300 µm		85.5
	150 µm		93.4

TABLE 6

CONCRETE MIX PROPORTIONS USED IN THE FIELD

Sydenham River Structure Deck
Mix Design Data

Westbound Hwy. 402

Control Mix	Dry Mass kg/m^3
Normal Portland Cement	355 kg
Sand	715 kg
Stone (19 mm)	1155 kg
Total Water	145.5 kg
	2370.5 kg
Admixture MBL 83*	469 mL/100 kg NPC
Air Entraining Agent MBAE 10	45 mL/100 kg NPC

Eastbound Hwy. 402

Test Mix	Dry Mass kg/m^3
Normal Portland Cement	265 kg
Slag	90 kg
Sand	680 kg
Stone (19 mm)	1190 kg
Total Water	142.5 kg
	2367.5 kg
Admixture MBL 83*	469 mL/100 kg NPC and Slag
Air Entraining Agent MBAE 10	55 mL/100 kg NPC and Slag

* Type WN Designated minimum dose 375 mL per 100 kg cement per MTC Form 1303, DS:100.2.

TABLE 7

FIELD TRIAL - AIR, SLUMP AND 28 DAY CYLINDER TEST RESULTS

	Control Concrete 100% NPC				Test Concrete 75% NPC 25% Slag			
Load	Air %	Slump mm	Mass+ kg	Comp. Strength 28 Days MPa	Air %	Slump mm	Mass+ kg	Comp. Strength+ 28 Days MPa
1	6.5	80	13.2	40.2	6.75	80	12.8	33.9
2	5.5	60	13.1	37.5	7.0	110	13.0	36.9
3	5.2	65	13.3	40.2	7.3*	80	12.9	33.7
4	7.0	100	12.9	34.6	6.2	90	12.9	35.7
5	6.6	80	12.9	34.6	Rejected - High Slump			
6	7.5	100	12.8	32.7	5.8	105	12.9	36.3
7	5.0*	60	13.2	37.8	7.0	125	12.9	39.0
8	6.0	60	13.1	35.9	7.0	110	12.9	35.1
9	5.8	100	13.1	35.3	7.0	90	12.8	32.6
10	5.2	75	13.2	35.7	6.0	90	12.7	37.1
11	5.0	90	13.1	37.0	6.3	90	12.9	37.6
12	6.4	75	13.1	38.6	5.8	95	12.8	34.6
13	X	X	13.1	38.2	6.6	110	12.9	34.4
14					6.0	100	12.7	35.0
15					7.5	80	12.8	35.3
MEAN	6.0	78.8	13.1	36.8	6.6	96.8	12.9	35.5
Standard Deviation	0.83	15.83	0.14	2.26	0.56	13.67	0.09	1.82
Coefficient of Variation %	13.9	20.1	1	6.2	8.6	14.1	1	5.1

X Not Tested - make up load 1 m^3

+ Average of Two Tests

* Loads selected for intensive testing

TABLE 8
RESULTS OF LABORATORY MIXES

Batch No.	Admixture Source	Portland Cemcnt Source	Slag % of Cementitious Material	Portland Cement kg/m^3	Slag kg/m^3	Total of NPC and Slag kg/m^3	Class of Concrete MPa	Eff. W/C Ratio %	Slump mm	Air Content %	Compressive Strength MPa***				Tensile Str. MPa
											Age				
											3d	7d	28d	90d	28d
888	MBL 83	196	0	352	-	352	30	0.40	80	5.7	27.1	29.9	35.3	41.6**	2.9
889	MBL 83	196	25	263	88	351	30	0.40	80	5.8	22.5	29.4	39.9	43.8**	4.1
890	MBL 83	196	50	175	175	350	30	0.40	90	6.2	14.7	23.8	37.8	40.1**	4.0
891	MBL 83	196	0	406	-	406	35	0.38	80	6.2	27.5	32.2	37.2	38.3	3.2
892	MBL 83	196	25	305	102	407	35	0.38	85	6.0	23.9	31.6	39.7	44.8	3.3
893	MBL 83	196	50	203	203	406	35	0.37	85	6.3	18.1	27.0	40.2	38.3	4.0
897	MB HC	196	0	352	-	352	30	0.40	80	6.3	28.9	34.7	39.7	44.5	3.5
898	MB HC	196	25	265	89	354	30	0.40	90	6.0	24.8	30.6	39.9	45.0	3.4
899	MB HC	196	50	178	178	356	30	0.39	90	5.7	17.8	27.1	38.0	49.1	3.5
901	MB HC	196	0	411	-	411	35	0.37	80	5.6	34.7	37.9*	42.7	51.4	3.5
902	MB HC	196	25	307	103	410	35	0.36	85	6.0	28.4	37.1*	45.1	49.9	3.8
903	MB HC	196	50	206	206	412	35	0.37	85	5.8	20.0	30.9*	43.8	50.3	3.8
905	MBL 83	195	0	350	-	350	30	0.40	80	6.5	23.6	26.7	31.3	34.9	3.1
906	MBL 83	195	25	264	88	352	30	0.40	85	6.2	20.1	24.1	33.9	41.1	2.9
907	MBL 83	195	50	176	175	351	30	0.39	85	6.5	14.7	23.4	36.7	41.1	3.2
909	MBL 83	195	0	410	-	410	35	0.35	75	6.3	29.4	33.9	39.3	46.5	3.5
910	MBL 83	195	25	306	102	408	35	0.36	85	6.5	24.6	32.0	39.6	45.1	3.5
911	MBL 83	195	50	207	206	413	35	0.35	85	5.6	15.9	25.6	36.5	46.4	3.5
912	MB HC	195	0	353	-	353	30	0.39	90	6.3	29.7	34.7	42.6	46.4	4.1
913	MB HC	195	25	267	89	356	30	0.39	90	5.7	23.4	31.5	43.1	46.1	4.3
914	MB HC	195	50	179	178	357	30	0.38	85	5.5	14.1	24.1	39.1	45.0	4.0
918	MB HC	195	0	411	-	411	35	0.35	75	6.3	33.1	38.6	41.0	52.6	4.4
919	MB HC	195	25	310	103	413	35	0.35	90	5.8	25.6	33.9	44.2	53.5	4.3
920	MB HC	195	50	208	207	415	35	0.34	90	6.0	17.2	27.5	45.7	53.5	4.2

Notes:- Cement Source 195 Canada Cement Lafarge Type 10
196 St. Marys (Bowmanville Plant) Type 10

Air Entraining Agent MB AE 10
* 8 day test
** 91 day test
90 day test - 1 cylinder only
*** 3, 7, and 28 day compressive strength test results, average of two tests

TABLE 9

28 DAY FLEXURAL AND TENSILE TEST RESULTS

	Flexural * Strength (Field Tests)	Split Tensile ** (Field Tests)	Split Tensile *** (Laboratory Tests)	
Class of Test Concrete	30 MPa	30 MPa	30 MPa	35 MPa
Mix Design				
100% NPC Control Mix (Load 7, 80 05 21)	5.69 MPa 5.52 MPa 5.31 MPa 4.79 MPa	3.50 MPa 3.50 MPa	2.9 MPa 3.5 MPa 3.1 MPa 4.1 MPa	3.2 MPa 3.5 MPa 3.5 MPa 4.4 MPa
Average	5.33 MPa	3.50 MPa	3.4 MPa	3.7 MPa
75% NPC 25% Slag Test Mix (Load 3, 80 05 22)	5.03 MPa 5.07 MPa 4.69 MPa 4.89 MPa	3.40 MPa 2.90 MPa	4.1 MPa 3.4 MPa 2.9 MPa 4.3 MPa	3.3 MPa 3.8 MPa 3.5 MPa 4.3 MPa
Average	4.92 MPa	3.15 MPa	3.7 MPa	3.7 MPa
50% NPC 50% Slag Test Mix			4.0 MPa 3.5 MPa 3.2 MPa 4.0 MPa	4.0 MPa 3.8 MPa 3.5 MPa 4.2 MPa
Average	-	-	3.7 MPa	3.8 MPa

* Test on 150 x 150 x 760 mm beams
** On 150 x 300 mm cylinders, refer to CSA A23.2-13C
*** Data also shown in Table 8

TABLE 10

AIR VOID SYSTEM PARAMETERS IN CONCRETE

		Plastic Concrete	Hardened Concrete (Cores)			
		Air Content in * Plastic Concrete %	Air ** Content %	No. of Voids/mm	Specific Surface mm^{-1}	Spacing Factor mm
	R.M. *** Load No.					
Control Concrete 100% NPC	2	5.5	5.8	0.34	23.19	0.19
	4	7.0	6.0	0.34	22.60	0.15
	5	6.6	6.4	0.36	22.54	0.19
	8	6.0	6.3	0.39	24.43	0.18
Test Concrete 75% NPC 25% Slag	2	7.0	5.5	0.37	26.85	0.18
	8	7.0	5.6	0.32	22.32	0.20
	11	6.3	5.2	0.41	32.00	0.15

* Total Air Determined by Pressure Method, M.T.C. Requirement 6.0% $\pm$ 1.5%

** Air Content Determined by Linear Traverse

*** R.M. No. The numbers in this column represent the loads of concrete referred to in Table 7. The horizontal lines compare the air void parameters in the plastic and hardened concrete for the loads that were tested.

TABLE 11

PULSE VELOCITY TESTS

Relationship of Compressive Strength to Pulse Velocity of Field Concrete Average of Three Moist Cured Concrete Cylinders							
Age in Days	Sample *	Pulse Velocity km/sec	Ratio Test/ Control	Compressive Strength MPa	Ratio Test/ Control	Rates of Strength Development compared with 28 days	
						Test	Control
7	Test	4.17	0.93	22.7	0.75	0.73	0.80
	Control	4.47		30.1			
14	Test	4.39	0.96	27.7	0.83	0.89	0.89
	Control	4.56		33.5			
28	Test	4.5	0.96	31.1	0.82	1.00	1.00
	Control	4.7		37.7			
90	Test	4.54	0.97	34.3	0.81	1.10	1.12
	Control	4.67		42.3			

* Test 75% NPC 25% Slag
Control 100% NPC

TABLE 12

HEAT OF HYDRATION

METHOD OF TEST ASTM C-186-78		
Material	Heat of Hydration (kJ/kg)	
	7 days	28 days
100% NPC	308	353
75% NPC 25% Slag	268	318
50% NPC 50% Slag	264	269